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Progress in Target Design for IFE for Ion Beams and Lasers

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Critical to the success of high gain ion beam driven targets for IFE is the tradeoff between target gain and the required focal spot size. A target design has been developed which uses the internal structure of the hohlraum to achieve radiation symmetry using beam spots with almost triple the allowed focal spot area relative to the earlier distributed radiator designs at comparable driver energy. An analysis is presented of the tradeoff between implosion robustness and the target fabrication specifications for survival against hydrodynamic instabilities during the implosion. A key issue for laser driven direct drive (DD) targets is control of hydrodynamic instability growth while achieving adequate gain for IFE. The goal of DD targets for IFE is to maximize gain through use of features such as wetted foams and laser zooming to increase absorption and use of a high-z coating to reduce laser imprint and achieve optimal control of instability growth. Because of advances in hohlraum design, laser driven indirect drive targets may have adequate gain for IFE for laser drivers with an efficiency of 10% or more. A key issue for the fast ignition concept is the ability to couple the hot electrons produced in high intensity laser matter interaction into the dense imploded core of an implosion. Indirect drive designs with a re-entrant cone make it possible to keep the dense core within about 100 μm of the laser absorption point.

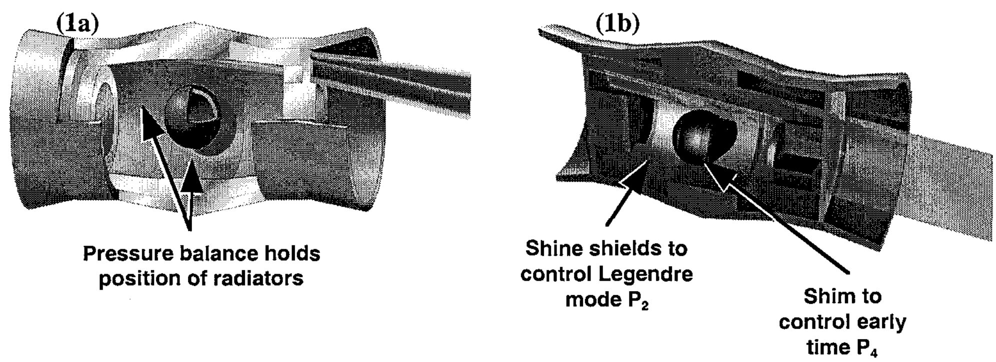
1. Introduction

Researchers in the U.S. are pursuing a wide range of target options for Inertial Fusion Energy (IFE) Applications. These include indirect drive and direct drive targets utilizing both central hot spot ignition and fast ignition. Drivers include Lasers, Ion Beams, and Z-Pinches. Each Target/Driver combinations has its advantages and disadvantages. For IFE applications, we must have $\eta G>7\text{-}10$, where G is the target gain G and η is the driver efficiency. Some combinations are further advanced than others and form the baseline approaches for IFE in the U.S.: 1) Two-sided Indirect Drive targets with hot spot ignition utilizing ion beam drivers; 2) Uniform Illumination Direct Drive targets with hot spot ignition utilizing either KrF or DPSSL lasers. A number of other combinations are being investigated at a lower level. Indirect Drive with lasers is well advanced in the US and forms the baseline approach for ignition on the US National Ignition Facility (NIF). Although the gain of the baseline NIF targets is inadequate for laser driven IFE, ideas are being explored which would significantly increase the gain possible with this approach. Fast Ignition has the potential for the highest gain and lowest driver energy of any approach currently being investigated for IFE. The compression phase for fast ignition can be driven by a wide range of drivers including ion beams, lasers, and z-pinches. However, the physics of laser matter interaction and transport of the energetic particles required for fast ignition is still poorly understood. Although the results are not covered in this paper, recent progress on z-pinches has also increased interest in their potential use for IFE.

2. Indirect Drive Ion Beam Targets

Critical to the success of high gain ion beam driven targets for IFE is the tradeoff between target gain and the required focal spot size. The current baseline targets for heavy ion beam drivers are two-sided indirect drive[1]. As shown in Fig 1a, these targets stop the ions in radiators distributed within the hohlraum to achieve symmetry. The placement of these radiators and the strategy for achieving

New symmetry control techniques allow target designs with larger spots for distributed radiator targets for heavy ion fusion



Distributed radiator target
Beam spot radius: 1.8 mm x 4.1 mm
Effective radius: 2.7 mm
5.9 MJ beam energy
Gain = 68

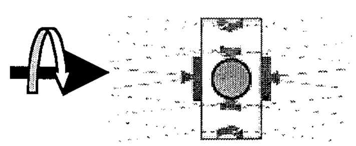
Hybrid target
Beam spot: 3.8 mm x 5.4 mm
Effective radius: 4.5 mm
6.7 MJ beam energy
Gain = 58

approach being followed for NIF. The symmetry is very similar to the target shown in Fig. 1a has a hohlraum whose size relative to the capsule is essentially the same as that for NIF. Since hohlraum symmetry is strongly affect by these relative sizes, this choice allows ion beam targets to benefit from the large data base developed for laser targets. The target shown in Fig. 1a has a gain of 68 with 5.9 MJ of beam energy. For expected driver efficiencies in the range of 25%, we have $\eta G>15$ which is adequate for IFE. Since these targets utilize low density radiators in combination with a low density low-z fill to maintain pressure equilibrium throughout the hohlraum interior during the length of the pulse, calculations indicate that the hohlraum can be smaller relative to the capsule than for the NIF baseline targets. Calculations of these "close-coupled" distributed radiator targets[2] indicate that is may be possible to get nearly twice the gain at half the energy relative to the target shown in Fig. 1a. The major challenge for ion beams in driving these targets is achieving the required spot sizes. The distributed radiator target utilizes an array of beams with elliptical spots that fill an annulus at each end of the target. The target in Fig. 1a requires spots that are 1.8 mm in minor radius and 4.1 mm in major radius. The close coupled design requires even smaller spots. The highest priority research in target designs for ion beam drivers is on concepts which allow larger spot sizes. Shown in Fig 1b is a recent design[3] dubbed the hybrid target. Earlier ion beam targets utilized radiators located at the ends of the hohlraum and attempted to rely on internal structure in the hohlraum to achieve symmetry[4]. However, motion of material in the end radiators made symmetry very difficult to achieve. The hybrid design combines features of the end radiator target and the distributed radiator targets to achieve symmetry. This design accommodates beam spots that nearly fill the entire end of the hohlraum. As indicated in figure 1b, the spots required by the hybrid target have nearly 3 times the area as that required for a similar sized distributed radiator target. These targets are about 14% less efficient than the distributed radiator target because of radiation transport losses around the end shield. In addition, achieving long wavelength symmetry to the 1-2% level in flux requires used of some internal hohlraum structure in the hybrid design. The end shield is made partially transmissive to radiation to control the P2 legendre moment of flux and a banded shim near the capsule is needed to control an early time asymmetry in P4. Hydrodynamic instability effects of this banded P4 shim are being investigated.

Fig. 2 - By using the symmetry control techniques we are developing, we can design alternate geometry hohlraums and beam illumination approaches that accept very large beam spots

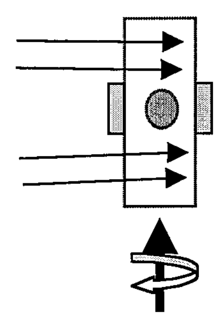
(2a)

Tuna can



(2b)

Illumination through one side of hohlraum



By using a hohlraum shaped like a tuna can instead of a soup can, very large beam spots are possible

Status:
Simple scaling laws predict 7-8 MJ of beam energy with up to a 7 mm radius spot and gain ~ 50-60

Spot size ~ 5 mm radius
Baseline spot ~ 1.7 mm radius

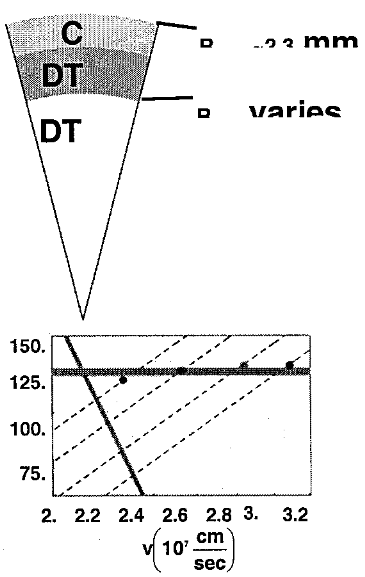
3-D geometry can be calculated with ASCI codes which have been modified to include ion beam deposition

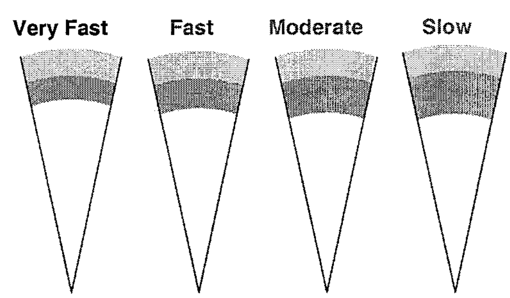
Other target and beam geometries may further relax the spot size requirements. Hohlraums designs to date have largely followed the work done for NIF. These hohlraums are shaped like a “soup can” with a length almost twice the diameter. It may be possible to achieve adequate symmetry in hohlraums with the opposite aspect ratio, a “tuna can” hohlraum, as indicated in Fig. 2a. A target such as this would permit a further increase in spot size although again, some internal hohlraum structure would be required to achieve symmetry.

There would be a significant advantage to ion beam targets which could achieve adequate implosion symmetry with single-sided rather than double-sided illumination. This would eliminate the need for bending the ion beams and would significantly simplify the accelerator architecture. In general, the analysis of such targets requires 3D radiation hydrodynamics codes. Such codes are becoming available in the US because of the Accelerated Strategic Computing Initiative (ASCI). One possible target of this type is indicated in Fig. 2b.

Several authors have looked at the scaling of the ignition threshold for ICF targets[5-7]. Under real world constraints, targets cannot operate exactly at the ignition threshold. For example, to accommodate imprecision in target fabrication, and asymmetry, there must be some ignition margin. This means that a target with a given mass and fuel entropy must have an implosion velocity somewhat above the minimum required for ignition. But there is a gain penalty for having too much margin. Also hydrodynamic instability places an upper limit on the implosion velocity or margin that can be achieved with a given drive pressure. So there is an optimum margin. Although there is currently no comprehensive model for identifying this optimum, it is possible to identify an optimum for a specific set of capsules[8]. Fig. 3 shows a series of capsules which would be appropriate for either hohlraum shown in Fig. 1. These capsules are all driven at 265 eV and all absorb about 900 KJ of energy. The margin in implosion energy above the ignition threshold varies from about 10% for the slowest most massive capsule to 90% for the fastest capsule. The fastest capsule is the thinnest

Fig. 3 - Capsule with varying thickness fuel layers are used to explore the robustness to hydrodynamic instabilities as a function of 10 ignition margin

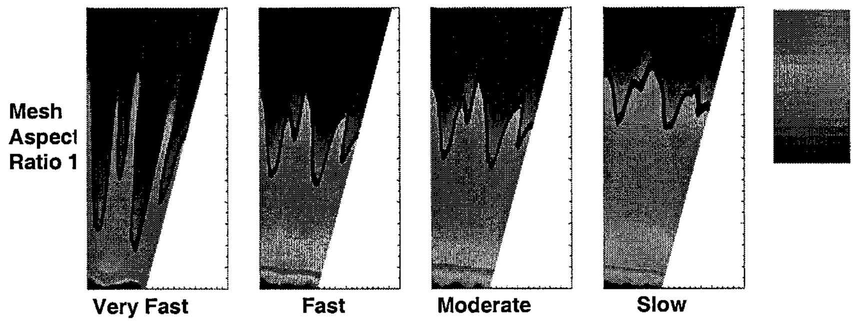




E_{ABS} ~ 900 kJ
$Tr)_{max}$ ~ 265 eV

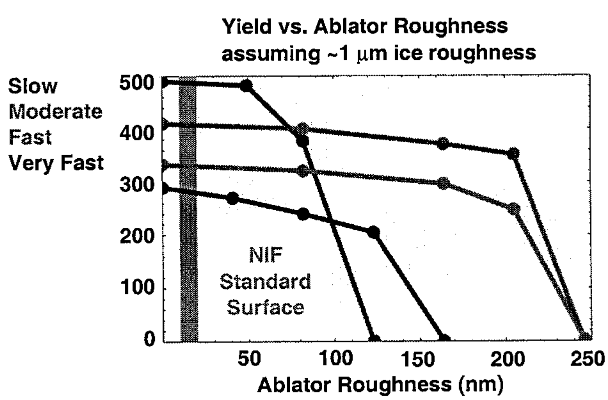
Problem Name	*Very Fast*	*Fast*	*Moderate*	*Slow*
Mass of fuel (mg)	2.7	3.2	3.9	4.6
v_{imp-mw}(10^7 cm/sec)	3.1	2.8	2.5	2.3
Yield (MJ)	286	333	412	496
IFAR	50	45	38	26
E/E_{ign}	1.8	1.6	1.3	1.1

Fig. 4 - Multimode simulations show the fastest capsule is nearing shell breakup before stagnation while the slowest capsule is much less perturbed. All four capsules with 80 nm ablator and 1 μm ice finish.



and has the largest in-flight-aspect-ratio (IFAR) which is the ratio of the capsule radius to its thickness, quoted here at 3/4 of the initial capsule inner radius. This capsule is the most sensitive to hydrodynamic instabilities during the implosion process. The slowest capsule is the thickest and the least sensitive to perturbations during the implosion process. Results of multimode instability calculations are shown in Fig. 4 near peak implosion velocity. The fastest capsule has nearly broken up while the slowest capsule is only mildly perturbed. On the other hand, the slowest capsule has the least margin and takes the longest to ignite during the compression phase. This delay allows perturbations seeded during acceleration to grow to larger amplitude for the slowest capsule than for the faster capsules . For this set of capsules there is an optimum roughness as indicated in Fig. 5. The two intermediate velocity capsules can tolerate about a factor of two larger initial

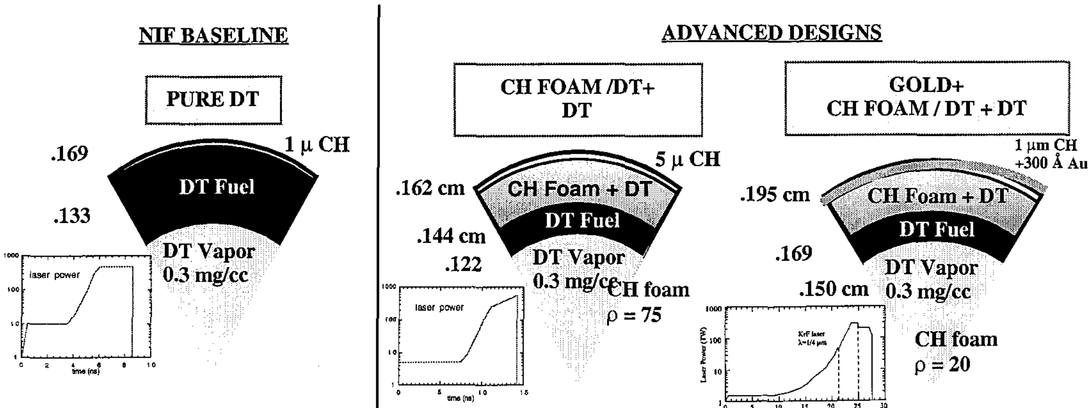
Fig. 5 - For the set of capsules from Fig. 3 there is an optimal "robustness" with about a 30% ignition margin. High yield plastic capsules can tolerate ablator roughness ~ 10-20x NIF standard.



For this configuration:

- Slow capsule fails due to mix of cold fuel into the hot spot
- Very fast capsule fails due to "shell breakup"
- Moderate and Fast capsule (Margin 1.3-1.6) are most robust (NIF capsule margin 1.3-1.4)
- Slow capsule gives highest gain for roughness <80nm

Fig. 6 - The NIF baseline direct drive (DD) target use pulse shaping to adjust fuel entropy as a strategy for controlling hydrodynamic instability growth. Advanced designs use foams and laser zooming to increase absorption. A high-z coating is added to reduce laser printing.



Laser Type	Glass(_=0.35mm)	Glass(_=0.35mm)	KrF(_=0.26mm)	KrF (ISI)
Laser Energy	1.6 MJ (~60% absorbed)	1.6 MJ (~85% absorbed)	1.6 MJ	1.3 MJ
1-D Gain	23	45-120	108	127
Zooming	No	No	Yes	Yes
ρR_{max}	1.2	1.86	2.11	1.8
e-folds_{max}	4.7	4.8	6.1	8
Ref:	C. Verdon UR	NRL	NRL	NRL

For NIF baseline, see S.V. Weber et al. Phys Plasmas 4, 1978 (1997), also S. E. Bodner, et al, Phys Plasmas 5, 1901 (1998)

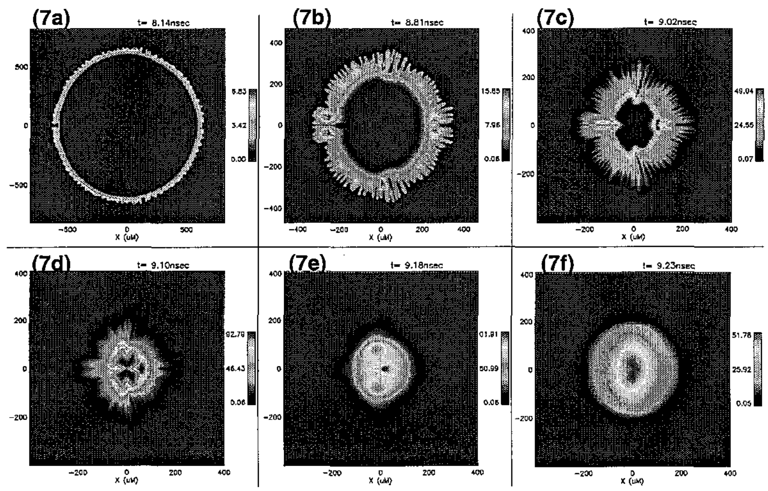
surface perturbation than the fastest or slowest capsules. However, even the slowest capsule, with a 10% ignition margin can tolerate a significantly larger perturbation than NIF capsules. Ultimately there will have to be a tradeoff between gain and a relaxation in the precision required in fabrication or in implosion symmetry.

3. Direct Drive Laser Targets

A key issues for laser driven direct drive (DD) targets is control of hydrodynamic instability growth while achieving adequate gain for IFE. Shown in Fig. 6 are a trio of laser driven direct drive capsules. The capsule in 6a, designed by Verdon[9] is the current NIF baseline capsule for direct drive. Direct drive capsules in general have a higher coupling efficiency from laser light to compressed fuel than indirect drive capsules. However, they have a mass ablation rate that is lower by a factor of 5-10 than indirect drive targets at a given intensity and they also have sharper density gradients. As a result, direct drive targets at a given entropy are more susceptible to hydrodynamic instabilities than indirect drive targets. In addition, directly irradiated targets are susceptible to imprint from short spatial scale intensity variations which adds another source of perturbations. The approach taken to reduce the effects of hydrodynamic instabilities is to implode the capsule with higher entropy in the unablated shell. This thickens the shells and increases the ablation velocity. This higher entropy reduces the gain achievable with a given energy into the fuel and at least partially offsets the coupling efficiency advantage of direct drive. The critical question for direct drive targets for IFE is the degree to which the entropy must be increased to achieve adequate stability.

The NIF baseline target in Fig. 1a uses shock timing during the drive pulse to set the shell entropy. The entropy is often characterized by the ratio α of the pressure required for a given density compared to the Fermi degenerate minimum. For the shell in Fig 1a we have α~3 and the 1D gain is calculated to be 23. Even at this entropy level, the growth of hydrodynamic instabilities is significant. Both Rochester and NRL have carried out 2D instability calculations on this target. The most complete calculations, by NRL[10], include the estimated long wavelength effects on NIF of laser power imbalance and pointing errors as well as short wavelength effects up to Legendre mode l=128 from capsule fabrication roughness and laser imprinting. The results of these calculations are shown in Fig. 7. Although the yield is degraded from the 1D calculations to a gain of 18, the target is calculated to ignite and burn. Fig. 7b shows that the shell is near breakup at peak velocity. Since this target is susceptible to modes up to about l=300, calculations with even more resolution are being carried out.

Fig. 7 - A calculation of the NIF baseline DT pellet using the NRL Fast 2D code which resolves modes 2-128 with inner and outer surface roughness, beam imbalance and 1 THz optical smoothing, gives gain = 18



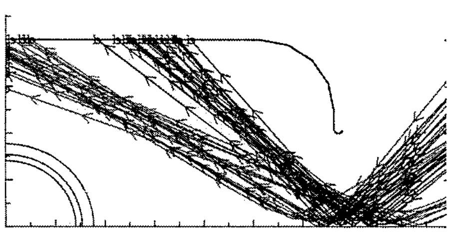
The time integrated absorption for the target in Fig. 6a, which is nearly pure DT, is only about 60%. At early time, when the spot size of all the beams is nearly equal to the capsule size, the absorption is high. However, at the intensities on the target of about 10^{15} W/cm^2, the absorption drops when the critical density moves inward during the pulse. The wetted foam target in Fig. 6b helps mitigate this effect. The inverse Bremsstrahlung in the foam is sufficiently high that the integrated absorption is about 85%. With all else the same, this higher absorption, A, would about double the gain achievable on NIF since gain G~$A^{5/3}$ at fixed laser energy[11]. Since the foam provides an additional method for controlling the density distribution within the shell, it may be possible to further reduce instability growth and achieve higher gain than predicted by the increased absorption alone. In 1D, gains as high as 120 have been calculated. Multimode 2D calculations have not yet been carried out but analytic estimates[12] suggest that gains between the peak 1D gain and a direct scale of the NIF Baseline target may be possible. Both NRL and LLE have looked at direct drive designs of this type. NRL has utilized the additional possibility of beam zooming in the KrF calculations as indicated in the summary below Fig. 6b. Beam zooming further increases absorption as the target implodes during the implosion. In beam zooming, the beam spot size is adjusted either continuously or in steps during the implosion to match the imploded capsule size.

Experiments[13] have shown that a thin high-z layer can reduce the imprinting of short wavelength laser nonuniformities. NRL has incorporated such a layer[9,13] in the target design in Fig. 6c. The high-z layer generates x rays that can preheat and expand the DT-wetted foam. This effect can reduce imprinting and also provides an additional technique for producing a density distribution in the shell which will minimize the growth of hydrodynamic instabilities. In 1D, NRL and LLNL calculate gains in excess of 120 for laser energies near 1 MJ if hydrodynamic instability can be controlled sufficiently to allow an α~1 implosion for the fuel. However, 2D instability calculations have not yet been carried out for this design.

4. Indirect Drive Laser Targets

In the NIF baseline indirect drive targets, about 11% of the 1.35 MJ of laser energy absorbed in the hohlraum is coupled to the capsule[11,14]. A number of design modifications have been identified[15] which can substantially increase this coupling efficiency as indicated in Fig. 8. These effects include using a cocktail hohlraum wall. A cocktail wall is a mixture of elements chosen so that opacities from the various materials overlap to fill holes in the opacity of a single material. Experiments are underway on the Omega laser to test material mixtures. Calculations also indicate that it is possible to reduce the size of the laser entrance hole and the size of the hohlraum for a given capsule size relative to that planned

Fig. 8 - Recent advances in design for targets indirectly driven by lasers have reopened this option for IFE



Peak laser power 300 TW

Laser energy ~2.3 MJ

$E_{capsule}$ ~ 600 kJ

Yield 175 MJ (in good symmetry limit)

Gain ~ 75

Increased hohlraum coupling efficiency is a combination of many small effects

Source	CE(%)
Point design	11
250 eV 7 ns	13
Entrance hole	15
~0.8 NIF baseline radius	
Cocktail wall	17
Cocktail + LEH*0.8	20
CE ~ 90% not 80%	22
$R_{hohlraum}/R_{NIF\ baseline}$	~0.9

for the NIF baseline target. With higher coupling efficiency it is possible to achieve adequate stability control with a lower drive temperature. This lower temperature results in a longer pulse with higher hohlraum wall albedo and a further increase in efficiency. A longer, lower power pulse allows NIF to generate more energy and drive a larger capsule. With a given ignition margin, a larger capsule will have a larger gain. The combination of all these effects makes it possible that gains over 70 could be achieved on NIF for indirect drive. Fully integrated 2D hohlraum calculations have not yet done that well. Initial calculations which use minor variations from the NIF baseline hohlraum and beam placement have about half this gain. With the reduced hohlraum size and long pulses required for the highest gain capsules, more work is required to achieve adequate symmetry. Many techniques including internal hohlraum structure as used in ion beam targets are available to achieve adequate symmetry and may even be compatible with gains higher than 70. At this gain, laser driven indirect drive targets may be adequate for IFE for laser drivers such as DPSSL's with a potential efficiency of 10% or more. Compared to the baseline direct drive targets being examined for laser driven IFE, indirect drive targets would have advantages for target injection, and may allow thick liquid wall chambers. For consistency with liquid wall chambers, the beam cone angles will need to be smaller than those on NIF which has beams coming in over a range of angles up to 50 degrees relative to the hohlraum axis. Target designs which produce x-rays in underdense radiators, positioned like those in the distributed radiator target for ion beams may allow beams that enter the hohlraum at much smaller angles.

5. Indirect Drive Cone Focus Targets for Fast Ignition

A key issue for the fast ignition concept is the ability to couple the hot electrons produced in high intensity laser matter interaction into the dense

Fig. 9 - A re-entrant tube and cone provide access for the ignitor beam to the imploded, compressed core for indirectly driven capsules.

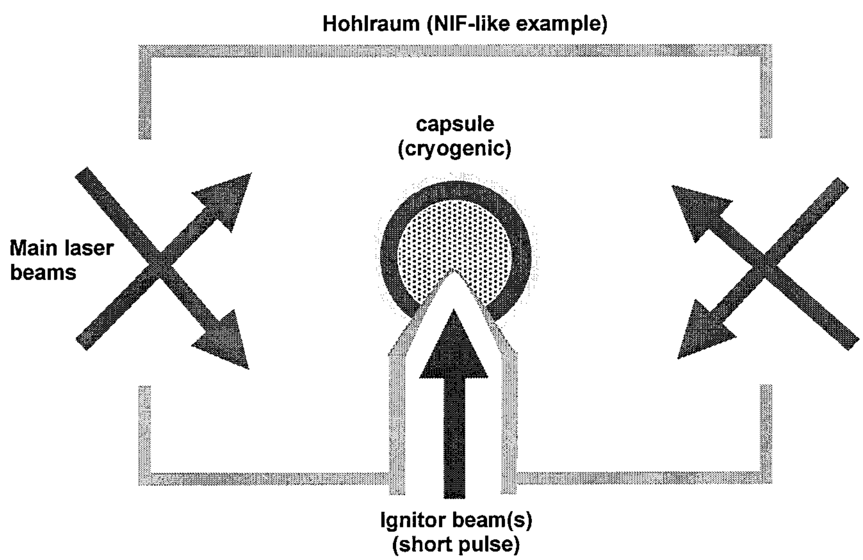
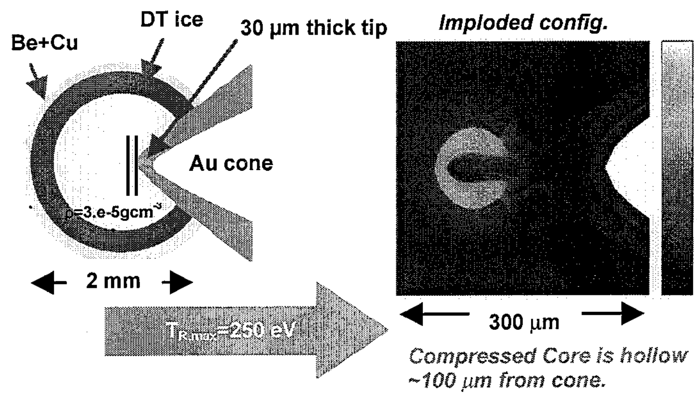
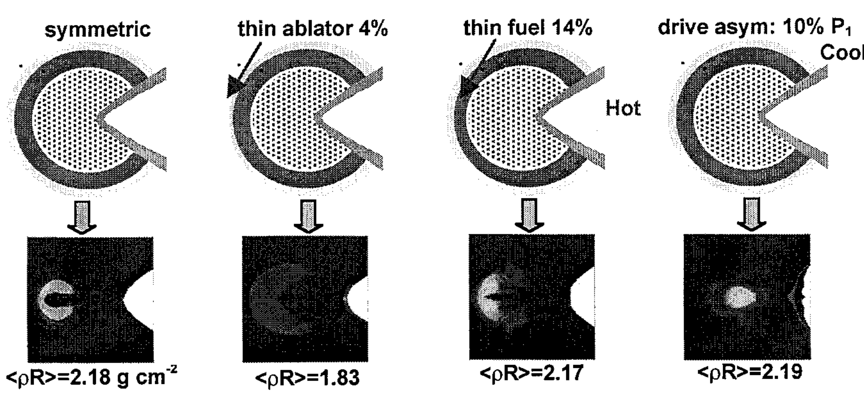


Fig. 10 - NIF scale capsule (absorbs ~180kJ*) can be imploded to $<\rho R>_{DT}$=2.18 g cm^{-2} in 2D calculations.
(*Expect 10% overall coupling efficiency, or better)



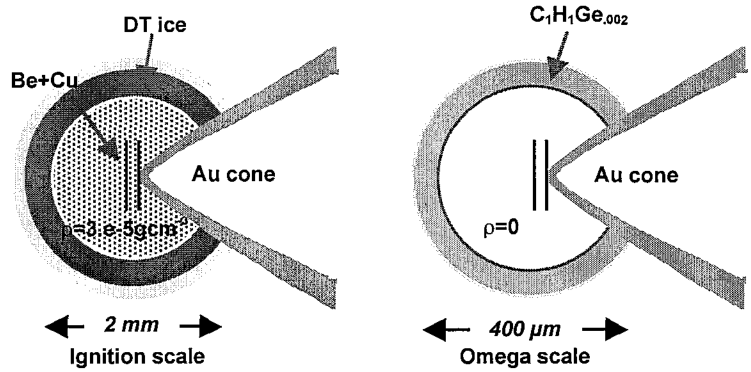
imploded core of an implosion. This is true for both direct and indirect drive schemes for producing the dense fuel core, but is particularly true for indirect drive since the ablation rates and hence the matter in the hot corona surrounding the dense core, are a factor of 5-10 more than for direct drive targets. Indirect drive designs with a re-entrant cone as indicated in Fig. 9 make it possible to keep the dense core within about 100 μm of the laser absorption point. This design approach was first proposed by Tabak[16,17] and is being pursued for both direct drive[18] and indirect drive. Although lasers are the only driver which can currently achieve the combination of power, pulse length and focal intensity required for the ignition beam, a wide range of drivers including lasers, ion beams, and z-pinches are suitable for fuel compression if indirect drive is used. An indirect drive cone focus fast ignition design[19] which could be tested on NIF is shown in Fig. 10. The imploded core has a ρr>2 which is adequate for ignition and burn propagation. The implosion calculation used a symmetric radiation drive and produces a hollow shell of dense fuel. Although this is desirable for a central hot spot ignition target, it makes fast ignition less efficient. A compressed core

Fig. 11 - Asymmetric capsule or drive - for faster implosion opposite cone - can eliminate the hollow core in the fuel assembly of a cone focus target.



without the hollow center can be achieved using an asymmetric drive[20] as shown in Fig. 11. Also, as shown in Fig. 11 asymmetric drive is more effective than an asymmetric shell in eliminating the hollow core in these calculations. Initial experiments to test indirect drive cone focus targets have been carried out on the Omega laser. The targets, as indicated in Fig.12, used a plastic shell about 1/5 the scale of targets that would be used on NIF. Radiography of the compressed core of plastic in these experiments was consistent with the calculations[21], although diagnostic noise resulted in relatively poor quality images and significant uncertainty in the compressed density.

Fig. 12 - Capsules for indirect drive cone focus experiments on Omega are plastic and about 1/5 the size of a NIF high yield design.



6. Conclusions

The program of research in target designs for IFE covers a broad spectrum of possible approaches. The current baseline approach with ion beams uses indirect drive targets. Critical to the success of high gain ion beam driven targets for IFE is the tradeoff between target gain and the required focal spot size. A target design has been developed which uses the internal structure of the hohlraum to achieve radiation symmetry using beam spots with almost triple the allowed focal spot area relative to the earlier distributed radiator designs at comparable driver energy. An important issue for IFE is the tradeoff between ignition robustness, which affects target fabrication requirements and gain. For specific indirect drive targets being examined for IFE, maximally robust targets have an ignition margin of about 30%. A key issue for the laser driven direct drive (DD) targets is control of hydrodynamic instability growth while achieving adequate gain for IFE. Baseline DD targets for NIF have inadequate gain for IFE. The goal of DD target design for IFE is to increase gain through use of features such as wetted foams and laser zooming to increase absorption and use of a high-z coating to reduce laser imprint and achieve optimal control of instability growth. Although current NIF indirect drive targets have gain well below that required for IFE, advances in hohlraum design may result in indirect drive targets with gain adequate for IFE for laser drivers with an efficiency of 10% or more. A key issue for the fast ignition concept is the ability to couple the hot electrons produced in high intensity laser matter interaction into the dense imploded core of an implosion. Indirect drive implosion designs with a re-entrant cone make it possible to keep the dense core within about 100 μm of the laser absorption point.

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